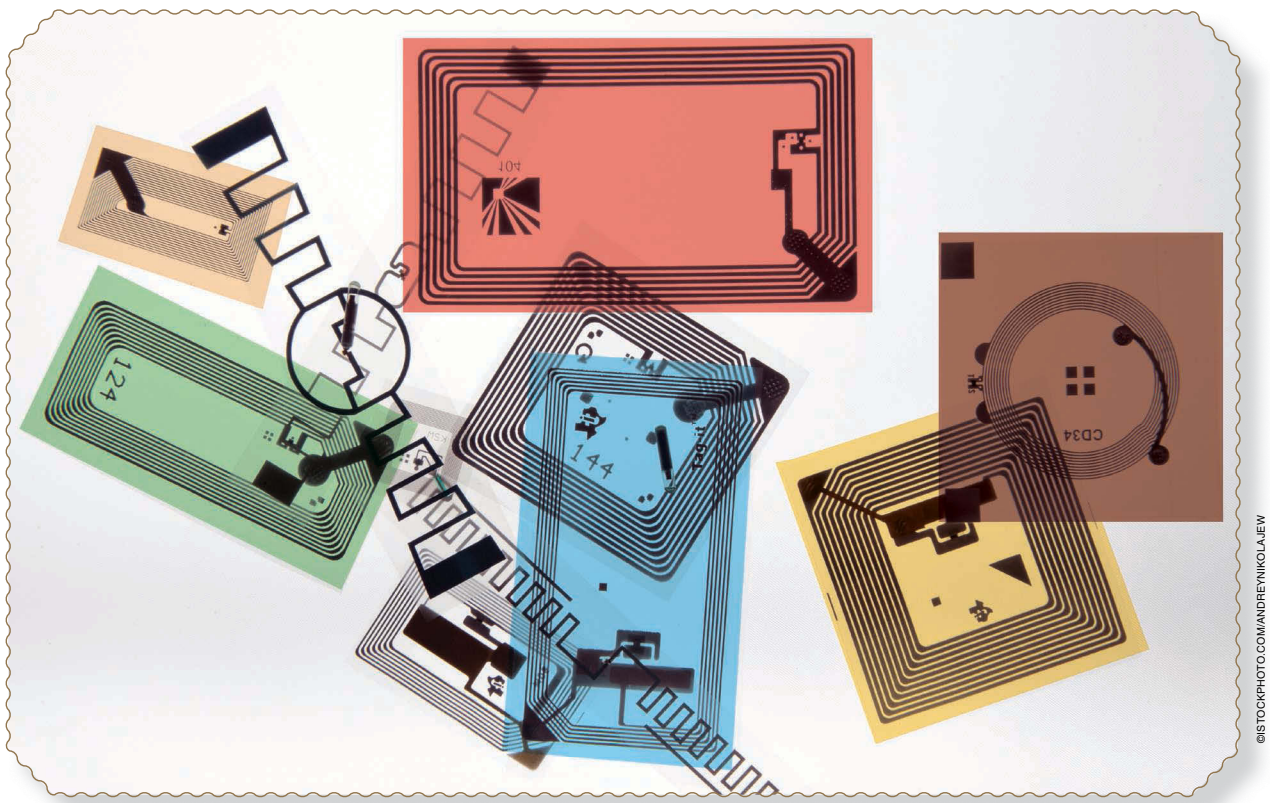




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Chipped Versus Chipless RF Identification

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RF identification (RFID) is a well-known wireless technology that has emerged for capturing data from a stationary or dynamic object. This is one of the key technologies poised to replace barcodes, which are low in data capacity and difficult to reprogram. To address this storage-of-data limitation, the silicon RFID chip was developed. Auto ID-based technologies such as optical barcodes and RFID address the function of “contactless” behavior,

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which eliminates the impracticalities of mechanical touch and enables the performance of defined tasks.

Data transmission through auto ID technologies has evolved over the past decade and is used in many applications, particularly for the retail industry. The evolution of RFID has allowed researchers to experiment with novel methods of communication between objects. As a result, chipless RFID—which works at microwave (MW) frequencies using the backscatter principle, compared to the chip’s total operation control in regular RFID system—has surfaced [1]. However, some industrial applications

represent specific circumstances where chipped RFID (i.e., RFID with a chip) performs better compared to chipless RFID. Both chipped and chipless RFID have the potential to transform the global retail industry. Many researchers and industry experts are interested in understanding the applicability of chipped and chipless RFID for retail applications, which we hope is one of the significant outcomes of this article.

Background of Auto ID Technologies

An in-depth analysis of auto ID technologies, (e.g., RFID technology) shows their usefulness in a broad spectrum of applications [1]. Smart cards, among the most popular applications of auto ID, also operate in a “contactless” paradigm with the help of near-field communication (NFC) technology; however, RFID technology is more adaptable as compared to other related technologies due to its ease of use. Several industries that use RFID technology are shown in Figure 1.

In a broader sense, both NFC and far-field communication (the latter is used for RFID) work on the same operational principles. NFC has arisen as a replacement for the magnetic stripe used in smart cards [2]; for example, it is capable of acting on behalf of a financial transaction’s credit/debit cards. One interesting aspect here is that NFC and RFID work on two fundamentally different principles: magnetic inductance and electromagnetism, respectively. Both technologies demand a tag/transponder, a reader/interrogator, middleware, and an enterprise application, as detailed in Figure 2.

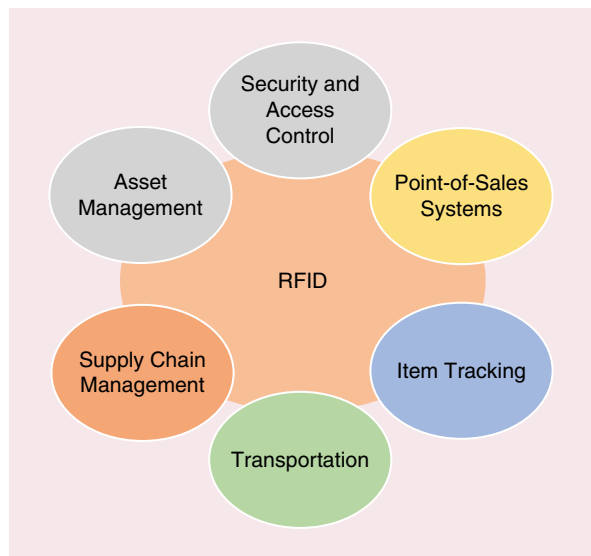


Figure 1. Representative RFID applications.

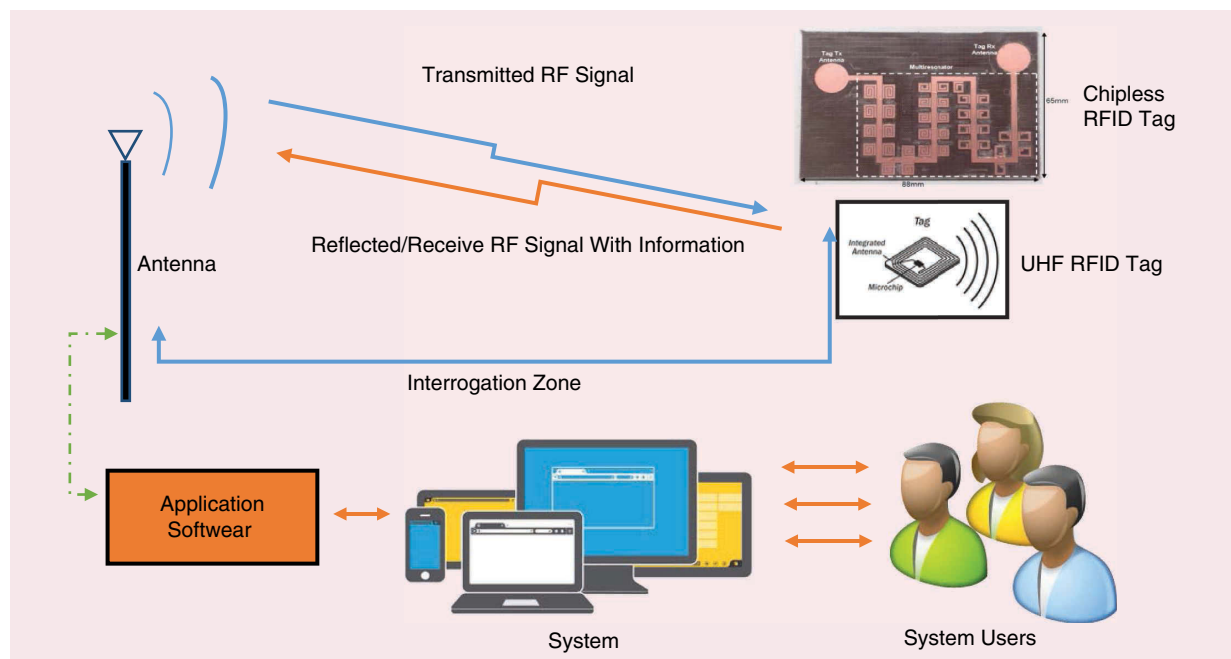


Figure 2. An RFID system.

RFID spans a wide variety of disciplines; as a result, multiple classifications have been assigned by different authors. In this article, the most prominent classifications of RFID are based on the frequency and internal power source. In the frequency classification, frequencies are segmented into low-frequency (LF), high-frequency (HF), ultrahigh-frequency (UHF), and MW frequency [3] tags (see Figure 3). We give more emphasis to UHF because most chipped RFID tags are used in the UHF range, while MW frequencies are considered as part of our review of chipless RFID. The other main classification is based on the tag's internal power source [4], as discussed in the following section.

Active RFID Tags

An active RFID tag has an internal microchip. Notably, these tags also have their own internal power source, which is used to power the integrated circuit (IC) and generate the transmitting signal to the RFID reader. In the RF industry, active tags are often called *beacons* because they broadcast their own signal. Compared to passive tags, active RFID tags have a larger memory, which is useful when the RFID reader is not able to immediately connect to a data source (e.g., database) to receive the information and is limited in size as a result of its need for a power source [5].

Semipassive RFID Tags

Semipassive RFID tags are similar to passive tags with the addition of a small battery. The additional

In the RF industry, active tags are often called *beacons* because they broadcast their own signal.

space allocated for the battery prevents semipassive RFID tags from achieving smaller dimensions compared to passive RFID tags. Unlike active tags, the tag's IC is powered by the transmission signal; however, the battery takes the action from there forward to send and receive signals. Thus, the received signal from a semipassive RFID tag is comparatively stronger than that of a passive tag's received signal [6].

Passive RFID Tags

Passive-type IC tags have no internal power supply. The minute electrical current induced in the antenna by the incoming RF signal is rectified and powers up the tag's IC to transmit a response signal. Although the communication range of a passive tag is short, such tags are compact in size and require no battery maintenance [7]. Passive RFID is the focus of this article; chipped RFID tags used in the UHF domain and chipless RFID in the MW range are introduced for comparison.

UHF RFID

UHF RFID is the most commonly used frequency range for most applications. UHF RFID technology was

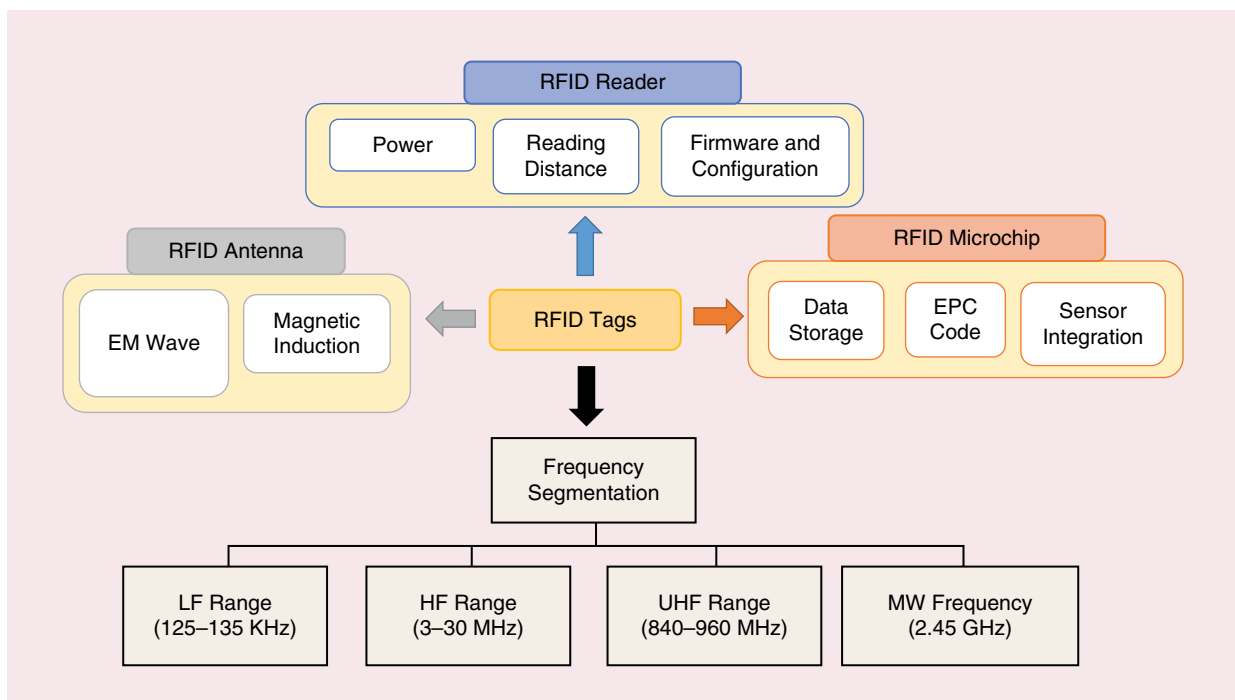


Figure 3. An RFID classification based on frequency segmentation. EPC: electronic product code.

introduced by retail giant Walmart [3] for the item-level tagging of products. Walmart's action put pressure on vendors in the supply chain to move from barcode to RF-based systems to comply with this new RFID use. The apparel industry also uses UHF RFID (e.g., Avery Dennison's AD226 UHF RFID tag, as shown in Figure 4) to tag cardboard vessels for identification purposes in inventory management. UHF RFID tags are prominent due to several benefits [3].

- UHF RFID tags prominently show an advantage in non-line-of-sight reading ability.
- The tags can reach up to a 20-m maximum reading distance.
- The tags allow comparatively higher data rates than LF and HF tags.
- The tags work using backscatter radiation of electromagnetic (EM) waves.

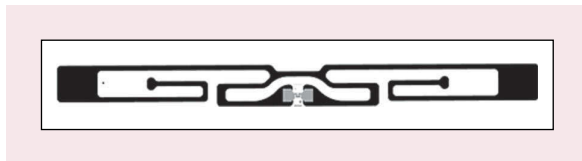


Figure 4. Avery Dennison's AD226 UHF RFID tag. (Source: AtlasRFIDstore.com; used with permission.)

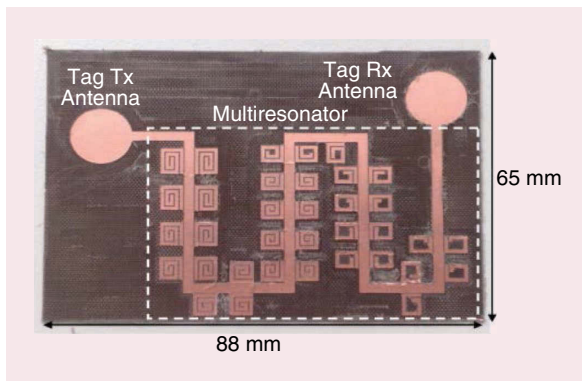


Figure 5. A 35-b chipless RFID tag. Tx: transmitter; Rx: receiver. (Source: S. Preradovic; used with permission.)



Figure 6. A chipless tagged can and milk carton.

- The tags can read multiple tags at one time (i.e., 300 tags/s).
- The tags are globally standardized under the mandates of the Electronic Product Code (EPC) Global, GATG, and CEPT, which helps with industry deployment.

In this article, we look at how UHF RFID principles have been applied.

Chipless RFID

The microchip plays a significant role in RFID. All RFID types, from LF to MW, carry a chip in their tag that can be excited by a signal coming from the transmitter or, alternatively, powered by a battery integrated into the tag itself [8]–[10]. Moreover, capabilities such as sensing, flexibility in operation, and versatility make the industry a part of the Internet of Things due to a chip in the tag [11]. However, there is also growing interest from industry about establishing a tag with no electronics in it, i.e., a completely passive tag. Chipless RFID tags work on a simple principle: a tag consists of a signature, and that particular signature is communicated to a reader antenna using the backscattering principle and EM waves. Because chipless RFID depends solely on radar principles, it is also called an *RF barcode*. Figure 5 shows an example 35-b chipless RFID tag containing a multiresonator and two antennas that communicate with the RFID reader.

Because it is completely passive, this tag opens the door for chipless RFID to be used in different applications at low cost (see Figure 5). For instance, sensing a meat package when it is stored below -4°C would be a challenging task with existing chipped tags because the IC's functionality may face issues in subzero temperatures. Chipless RFID technology also unlocks a wider spectrum of opportunities; for example, chipless RFID tags can be printed on any substrate (from paper-thin materials to hard metal), which may be difficult to accomplish with chipped RFID tags (see Figure 6). Because two distinct approaches are suggested for RFID technology (chipped and chipless), it is worth conducting a detailed review to clarify their distinct features. Such a review provides insights into the application of both types of RFID technologies for different applications.

Technology Review

The following sections discuss different parametric aspects and provide detailed comparisons of chipped and chipless RFID technologies.

Field of Communication

One of the key differences between chipped and chipless RFID is the site of their communication. The chip contained in chipped RFID provides more

flexible communication in close proximity or at a considerable distance (e.g., even for 15–20 m) [12]. However, in chipless RFID, the backscattering principle limits the distance a signal can travel due to environmental noise as well as regulations imposed on maximum power transfer across wireless mediums; hence, the operation of chipless RFID remains in the near field. For this reason, chipless RFID (in contrast to chipped RFID) is better suited for low-cost, near-field sensing applications.

Nature of Data-Capturing Mechanisms

As discussed in the “Background of Auto ID Technologies” section, chipped tags can be categorized as active, semipassive, and passive [9]. Other categorizations exist, based on read/read and read/write capability of the RFID tag IC, but, because there is no microprocessor on a chipless RFID tag, the tag’s read/read and read/write capability depends completely on the power coming from the transmitter antenna and the reflected power received by the reader antenna.

Based on this, chipless RFID tags can be further categorized as

- time-based reflectometry [13]
- frequency-based reflectometry [6].

Frequency-based reflectometry is popular among researchers because of its capabilities in both near- and far-field applications at higher frequencies. It is equally popular in the development of electrically small structures [14].

Data Storage Capability

The main industrial reason for keeping the RFID tag as simple as possible is to ensure ease of scalability at

a lower cost while still providing high data capacity. Chipped RFID can store more than 2 kB of data; however, it has also been shown that, for aerospace industry applications, 4–8 kB of data storage is possible in chipped RFID tags [15].

While chipless RFID provides the simplicity demanded by industry at a relatively lower cost, backscattering limits the data capacity a chipless RFID tag can provide because each bit must be identifiable by a specific frequency response. Therefore, achieving a higher bit rate (compared to chipped RFID tags) is virtually impossible. Researchers, however, have begun to investigate the possibilities of using multiple polarizations (e.g., horizontal and vertical or copolar and cross-polar) to increase the number of bits that can be identified for a given chipless RFID tag. For instance, the use of a 40-b tag has been experimentally confirmed [16], while the use of an 800-b chipless tag has been theoretically proven [17].

Reading Distance

Reading distance is often a key parameter demanded by industries, depending on the application. As an example, developing an RFID-based parking system in which individual vehicles are tagged by chipped RFID tags demands a higher read distance compared to a system designed for a retailer, which needs only a 50–100-cm reading range. Table 1 shows the different read distances achieved over various frequency ranges in both chipped and chipless RFID [10]. Attempts are being made to increase the reading distance of chipless RFID tags to 80 cm for some time-domain, reflectometry-based chipless tags [17]; 100-cm read distances for 4-dBm power levels have been mathematically proven [16].

TABLE 1. The different read distances achieved over different frequency ranges in both chipped and chipless RFID.	
Chipped RFID	
Frequency Range	Distance
LF range (125 kHz–134.3 kHz)	30 cm. The distance often depends on the size of the tag (e.g., a larger tag can detect from more than 2 m away).
HF range (13.56 MHz)	A distance of 1.5 m is acceptable; however, the reading range can be increased by multiport readers and special antennas, which can transmit more than 1 W of power.
UHF range (860–960-MHz) passive RFID tags	A distance of 1 m is considered the average reading distance; however, Gen 2 passive UHF tags can detect from up to 12 m away. Active and semiactive tags can reach distances of up to 50 m [11].
UHF range (433 MHz) active RFID tags	500 m. Used heavily in mining and healthcare applications [18].
Super HF range (2.45 GHz) active RFID tags	100 m [19].
Chipless RFID	
UWB range (3.1–10.6 GHz) [20]	Chipless tags operate in the UWB frequency range. UWB produces short pulses and low-power signals over a wide frequency spectrum, which is useful in short-range wireless communication [21].

UWB: ultrawideband.

The first UPCs were mostly implemented using LF RFID techniques.

The crucial constraint in both chipped and chipless RFID technologies is the performance degradation that accompanies increased read distances. In chipless RFID, this constraint is further aggravated; for example, the longer the communication path, the less likely it is to reflect back enough of a signal to the antenna to provide the necessary signal-to-noise ratio for the receiver’s signal processing algorithms. Increasing tag size was considered a way to improve the distance and performance; that is, for an identical-size tag, the power level may be limited by RFID regulations, which would undermine the tag’s performance.

Microchip Capabilities

The capabilities of microchips are important in chipped RFID tags, especially when the standardization of chipped tags has gone through multiple iterations since it was introduced as a Universal Product Code (UPC). The first UPCs were mostly implemented using LF RFID techniques [22]. Later, EPC emerged as the next generation of RFID (generation 2) and replaced UPC. EPC Global is the organization responsible for RFID standardization and also globally maintains RFID standards across industries for end-to-end supply chain systems. Generation 2, also known as *Gen 2*, defines the logical and physical requirements for RFID tags using backscatter principles. The latest RFID tags, which are commonly known as *Gen 3* and *Gen 4*, have shown 40% more sensitivity to RF interference and an improved reading distance of up to 16 m when used with passive UHF RFID tags under the maximum power allowed by U.S. Federal Communications Commission regulations (maximum power of 4 W) [23].

The capabilities of microchips, however, are not relevant to chipless RFID because they are not used. The three categories of chipless RFID tags are

- time-domain tags
- frequency-domain tags
- specific absorption rate (SAR)-based tags.

The performance of chipless RFID tags could be assessed by radar cross section (RCS) because the communication between the tag and reader is based solely on scattering principles similar to those of a radar system. At the same time, the quality factor (Q-factor), a dimensionless parameter, is also important for achieving compact tag structures with minimal material consumption and minimum energy losses [24], [25].

Reading Speed

Similar to reading distance, reading speed is critical in certain fast-moving applications. For instance, passive RFID tags attached to products for identification in a supermarket may need to be read quickly to meet the company’s inventory requirements. In the chipped RFID domain, the reading speed can vary based on the following parameters:

- reader capability
- tag polarization and orientation
- tag density (i.e., number of tags per location)
- tag material
- relative speed of movement between the antenna and tag
- antenna/reader configuration (antenna density/beam pattern)
- environmental conditions (e.g., harsh environments such as cold rooms or refrigerators).

Chipped tags can be detected at high speeds, such as on fast-moving trains and electric cars traveling at 80 km/h [22]. Chipless RFID tags, which are comparatively low in reading speed, have detected objects on moving conveyor belts at a speed of 80 m/min [26]. Table 2 summarizes the importance of RFID reading speed in different applications.

TABLE 2. Comparisons of reading speed technologies.		
Different Scenarios	Chipped RFID	Chipless RFID
Tagging automobiles	Chipped RFID is better suited because the UHF/HF RFID is not significantly influenced by the RCS of the automobile [27].	Chipless RFID is not suitable because the RCS generated by the metal surface of the automobile will hinder the tag signature.
Tagging products on a supermarket shelf	UHF RFID is already deployed in similar applications for clothing and supermarket retailers due to its advantage of non-line of sight and ease of inventory management.	Chipless RFID may provide a low-cost alternative to tagged products in retail environment [28].
Tagging laundry textiles	Microchips from the chipped RFID may not survive in a high-temperature/high-pressure environment.	Chipless RFID is better suited because the adequate encapsulation will guarantee the tag’s survival in dynamic environments [29].

Improvements in RFID tag readability are possible through signal processing and designing different tag capabilities applications, e.g., sensing.

Tag Density

Tag density is important in retail applications, especially when dealing with multiple tags at a given time. The readability of tags can vary based on

- tag size
- time duration between tag detection and the readers ability to avoid tag collision
- physical distance and arrangement of tags.

In one experiment [30], 1,000 chipped RFID tags/s were recorded at one time, but the chipless RFID tags could only be read one tag at a time, even though research has theoretically proven that three chipless RFID tags can be read at one time [31].

Application-Oriented RFID Tag Types (e.g., Retail)

Many tag types exist in the RFID domain for various applications. The two most commonly used tags are referred to as *label tags* [32], with which everyday items are tagged (e.g., grocery items), and *resin-formed tags* [33], used for special product items (e.g., inside metal and underground tracking).

In item-level tagging, chipless RFID tags can replace chipped tags [34]. Chipless tags are more reliable and cheaper in a retail environment and have the advantage of non-line-of-sight reading capability. However, chipless tags still struggle to enter the mainstream market due to their limited operational accuracy in noisy environments. Still, some researchers have suggested that using background calibration [35] and pseudo noise [36] could help improve read accuracy. The performance of chipless RFID is also affected by the presence of liquid [37] and metals, inherent constraints in any RF application. The use of ground dielectric antennas is popular in addressing these RF constraints.

Tag-Positioning Sensitivity

In terms of sensitivity, both chipped and chipless RFID tags remain largely dependent on multiple parameters in RFID systems, such as

- antenna polarity (linear or circular)
- tag-reading distance based on transmitted power
- tag collision when multiple tags are read at the same time
- tag material and its permittivity levels
- environmental considerations (e.g., reading tags in the presence of metal and/or liquids) [31].

Most tags and antennas developed in chipless RFID work with either singular polarization (usually linear polarization), where a tag needs to be on the same

Chipless RFID tags are a good alternative to chipped RFID tags for short-range applications.

orientation as the RFID antenna, or dual polarization, where the transmission antenna sends a signal in one plane and detects it in another perpendicular plane. Dual polarization can help increase the number of bits per tag. Developing orientation-insensitive tags has been an area of research interest, and an example of an orientation-insensitive, 32-b chipless RFID tag is shown in Figure 7 [38].

Sensitivity to Dirt/Mist/Corrosion

In an industrial environment, the existence of foreign particles can be a distraction to RFID tag detection. In cold chain applications, for example, it may be difficult to detect an RFID tag attached to packaged food because of the deposition of frost. With chipped RFID tags, performance depends mainly on the microchip in the tag; the microchip's operation in harsh environments will determine the application's robustness.

Chipless RFID tags are a good alternative to chipped RFID tags for short-range applications. The absence of a microchip in a chipless tag allows these RFID tags to perform better in harsh environments; however, chipless RFID tag performance may be affected by the presence of corrosion. Lower-cost chipless RFID tags often use metal MW laminates such as FR 4 and Taconic [39], which are prone to corrosion. Such a limitation can be addressed by printed conductive tags, that is, chipless RFID tags fabricated by means of printing techniques such as screen printing, rotogravure, flexography, and inkjet printing [40]. Such flexibility in chipless RFID has even made possible the use of chipless RFID inside buildings as well as for agriculture-plus-technology applications [41]. One challenge for use in this application is that any change in

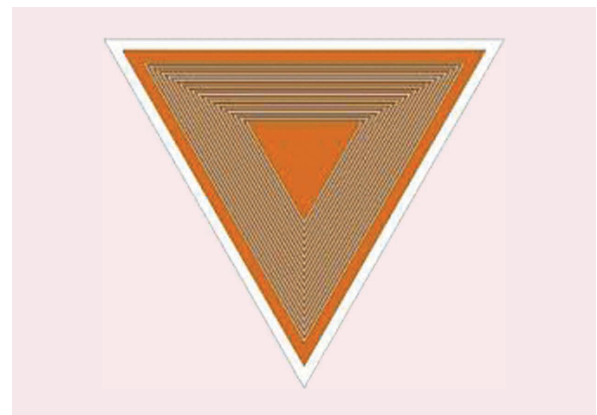


Figure 7. An orientation-insensitive chipless RFID tag [58].

When integrated with barcode scanners, handheld readers can perform both RF and barcode reading simultaneously, enabling multiple applications.

the microenvironment can significantly change the readability of a chipless tag. Some of these readability issues can be overcome by increasing the sensitivity of the RFID reader as well as by careful tag calibration.

Material Selection in Tag Development

The chip of the chipped RFID tags is usually produced using silicon on a wafer-by-wafer basis [26], although there are some instances where copper lithography or inkjet printing is used [42]. The rise of printing technology (e.g., screen printing) has also proved reliable in mass-scale deployment with relatively low cost [43].

Screen printing technology shows promise for the widespread deployment of chipless RFID tags [44]. The whole tag can be made at once using various printing techniques because there is no electronic component attached to it. In most current chipless RFID research, copper lithography is used as a platform to develop copper-based tags, which provide higher RCS and high Q-factor even though the process

is comparatively expensive considering that of screen printing. Another major advantage of using screen printing for chipless RFID tags is its ability to print on any surface, making it applicable to multiple industries (e.g., food packaging).

Tag Cost

Chipless RFID tags have served as a low-cost alternative to chipped RFID tags, where one tag can be produced for as little as AUD\$0.01; however, the cost depends primarily on volume and material consumption during the production process. For instance, the use of printing technology is even less expensive for chipless tags in larger-volume production (e.g., roll-to-roll processing). The average cost of a chipped RFID tag is AUD\$0.12–1.00. The exact cost is highly dependent on size, material consumption, purchase volume, and tag capabilities [45].

Types of RFID Readers

RFID readers perform the interrogation of RFID tags and extract desired data from the backscattered tag response. RFID readers usually consist of an RF section connected to a transmitter/receiver antenna and control and display units, as shown in Figure 8. Chipped RFID readers are widely available for a variety of commercial applications; some are able to deal with application interfaces through middleware, while others can handle multiple antennas simultaneously [46]. RFID readers can be divided into the following categories:

- power supply [47]
- interface used for communication [48]
- reader mobility
- tag-frequency response and protocols.

The two most relevant reader categories for this comparison, mobility and frequency response, are explained in the following sections.

Mobility-Based Classification

Stationary RFID Readers

Known as *fixed readers*, stationary RFID readers (Figure 9) can be mounted on objects such as walls, portals, and doors, where they are able to perform effective tag readings. Stationary readers are used in many applications, such as supply chain management, asset tracking, and personnel identification and authentication, where data are captured wirelessly. Fixed readers can also perform using multiple antennas simultaneously to achieve diverse radiation patterns [49].

Handheld RFID Readers

Handheld readers have built-in antennas and are usually battery powered (Figure 10). These readers have

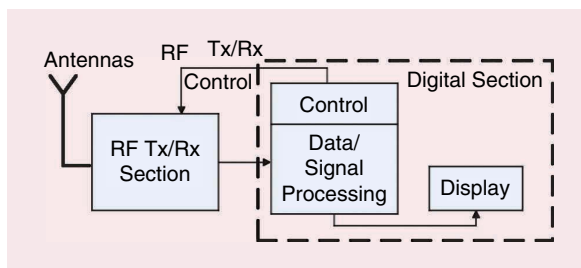


Figure 8. An RFID reader block diagram. (Source: A. Islam; used with permission.)

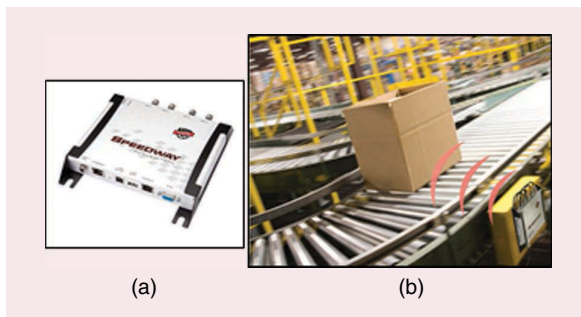


Figure 9. Stationary RFID readers: (a) an RFID reader connected to four omni-directional antennas and (b) an RFID reader mounted on a conveyor belt.

a shorter read range compared to stationary readers and are used for item-location tracking in warehouses [50]. When integrated with barcode scanners, handheld readers can perform both RF and barcode reading simultaneously, enabling multiple applications.

Transponder Frequency-Response-Based Classification

Unique Frequency-Response-Based Readers

These RFID readers operate with narrow bandwidths in the HF–VHF range (i.e., lower than 80 MHz) and use unique frequencies for both data transmission and reception.

Nonunique Frequency-Response-Based Readers

Operated among multiple frequency ranges and usually with wide bandwidths, these readers use two separate RFs to allow fast and reliable communication.

The classifications discussed previously provide insight into how RFID readers can be designed to meet specific requirements in a given application or otherwise generalized for mass-scale applications. Flexibility, accuracy, ability to diversify in harsh environments, and ease of integration are key considerations when selecting an RFID reader for modern-day applications. Similarly, chipless RFID readers can be classified as time-domain-, frequency-domain-, and SAR-based readers [51].

Time-Domain Readers

Time-domain-based chipless RFID tags use reflected echoes or a stream of pulses reflected from the tag to encode the data. The tag-reading process involves the generation of an interrogation signal, the capture of signals received from the tag, the processing of signals, and decoding the tag ID or data bits encoded in the tag.

Frequency-Domain Readers

Frequency-domain chipless tags use the frequency response's amplitude, phase, or both to encode data on the tag [52]. These specific signal characteristics are accessed by frequency-based RFID readers, which identify data through signal processing techniques. According to the technique used to encode data on the tag, the reading process and reader architecture differ [53].

SAR-Based Readers

An SAR-based chipless RFID system was developed by Spectral System Corporation [51]. Its tag consists of a substrate layer patterned with several diffraction elements on the order of the RF signal wavelength. An

The cost of a chipped RFID reader is determined mainly by the cost of hardware components and RF performance.

SAR reader connects to a large, multiarray antenna structure, and the reflected signal is processed to build an image using surface acoustic waves signal processing techniques.

The hardware and related middleware required with chipless RFID tags is more expensive than the tags; therefore, enormous potential exists to invest in research to develop a low-cost chipless RFID reader in ultrawideband (UWB) [54]–[56]. Much of the related work in this area uses expensive laboratory equipment such as vector network analyzers, RF signal generators, spectrum analyzers, and digital signal oscilloscopes for the purpose of tag interrogation and signal reception, which may not be suitable for use in a real industrial environment. Further research is necessary to develop a low-cost chipless RFID reader system that has better reading speed to bring chipless RFID technology into the mainstream.

Reader Cost

The cost of a chipped RFID reader is determined mainly by the cost of hardware components and RF performance. The cost ranges from AUD\$500–2,000 [57] based on performance functionalities such as

- reading speed
- number of antennas that can connect to the reader simultaneously (number of ports available)
- reader interface
- middleware connectivity.



Figure 10. A battery-powered handheld chipless RFID reader prototype. (Source: MMARS Lab, Monash University, Melbourne, Australia; used with permission.)

TABLE 3. A comparison of chipped and chipless RFID tags.

Parameters	Chipped RFID	Chipless RFID
Data-capturing mechanism	Passive backscattering principle	Passive backscattering principle
Reading distance	An average of 30 cm–12 m	1 m in the UWB frequency range
Reading speed	80 km/h	4.8 km/h
Microchip capabilities	UPC Gen 2, 3, and 4 used for higher sensitivity and better reading distance	No microchip used
Tag density	1,000 tags at once	Three tags at once
Tag-positioning sensitivity	Antenna polarity, tag-reading distance, tag collision, and material selection	Singular, dual polarization, and polarization insensitive
Sensitivity to dirt, mist, and corrosion	Depends on IC performance	Promising outcomes with printed chipless tags
Material selection in tag development	Introduction of silicone for chips and tags using either copper lithography or, if printing, inkjet printing or screen printing	Copper lithography and/or screen printing
Cost of a tag	AUD\$0.12–1.00	AUD\$0.01 (cost depends on volume and material consumption)

The realization of a commercially viable chipless RFID reader that operates in UWB may cost roughly AUD\$500–1,000.

Conclusions

This article provided an overview of chipless and chipped RFID and was carried out to help explain the fundamental differences between the technologies as well as their uses for diversified retail applications (see Table 3). It was shown that chipped RFID tags have many more applications than chipless RFID tags do. Applications using chipped RFID tags have also progressed faster than those of chipless tags because of the current availability of robust hardware and software platforms. In retail applications, chipped RFID can be very useful in item-level tagging for tracking purposes; however, chipless RFID is more robust in food-sensing applications, where the environment has minimal influence over mist and frost in extremely cold temperatures (e.g., the microchips of chipped RFID tags). It is important to consider all of the factors mentioned here, along with the technological possibilities, prior to selecting the right technology for the right industrial application.

References

- [1] N. Karmakar, S. Preradovic, and I. Balbin, "RFID transponders," *IEEE Microw. Mag.*, vol. 9, no. 5, pp. 90–103, Oct. 2008.
- [2] CommBank, "CommBank tap & pay." Accessed on: Mar. 17, 2018. [Online]. Available: <https://www.commbank.com.au/personal/online-banking/commbank-app/tap-and-pay.html>
- [3] P. Z. Nemaï Karmakar and M. Kambukage, "FPGA-controlled phased array antenna development for UHF RFID reader," in *Handbook of Smart Antennas for RFID Systems*, P. N. Karmakar, Ed. Hoboken, NJ: Wiley, 2010. doi: 10.1002/9780470872178.ch2.
- [4] S. Park and S. Hashimoto, "Autonomous mobile robot navigation using passive RFID in indoor environment," *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2366–2373, 2009.
- [5] Omni-ID, "The evolution of active RFID." Accessed on: Mar. 3, 2018. [Online]. Available: <https://www.omni-id.com/active-rfid-tags/>
- [6] T. H. Li, A. Borisenko, and M. Bolic, "Open platform semi-passive RFID tag," in *Proc. Ad-Hoc, Mobile, and Wireless Networks, 11th Int. Conf., ADHOC-NOW 2012, Belgrade, Serbia, July 9–11, 2012. (Lecture Notes in Computer Science, vol 7363)*, X. Y. Li, S. Papavassiliou, and S. Ruehrup, Eds. Berlin: Springer, 2012, pp. 249–259.
- [7] T. Q. V. Hoang, D. H. N. Bui, T. P. Nguyen, T. P. Vuong, and C. Defay, "Passive battery-free UHF RFID tag for athermic car windshields," in *Proc. IEEE Int. Symp. Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2017, pp. 643–644.
- [8] Y. F. Weng, S. W. Cheung, T. I. Yuk, and L. Liu, "Design of chipless UWB RFID system using a CPW multi-resonator," *IEEE Antennas Propag. Mag.*, vol. 55, no. 1, pp. 13–31, 2013.
- [9] K. F. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*, 3rd ed. Hoboken, NJ: Wiley, 2010.
- [10] D. Dardari, R. D. Errico, C. Roblin, A. Sibille, and M. Z. Win, "Ultrawide bandwidth RFID: The next generation?" *Proc. IEEE*, vol. 98, no. 9, pp. 1570–1582, 2010.
- [11] N. Javed, A. Habib, Y. Amin, and H. Tenhunen, "Towards moisture sensing using dual-polarized printable chipless RFID tag," in *Proc. Int. Conf. Frontiers of Information Technology (FIT)*, 2017, pp. 189–193.
- [12] C. Faulkner, "What is NFC? Everything you need to know." TechRadar, May 9, 2017. [Online]. Available: <http://www.techradar.com/news/what-is-nfc>
- [13] M. R. A. Shareef, M. A. Ashraf, O. M. Haraz, H. M. Behairy, and S. Alshebili, "Time analysis of frequency coded chipless RFID tag based on CPW multi-band resonators," in *Proc. 17th Int. Symp. Antenna Technology and Applied Electromagnetics (ANTEM)*, 2016, pp. 1–2. doi: 10.1109/ANTEM.2016.7550138.
- [14] Dassault Systems, "CST—Computer simulation technology." Accessed on: Mar. 5, 2018. [Online]. Available: <https://www.cst.com/products/cstmws/solvers/frequencydomainsolver>
- [15] RFID Journal, "How much information can an RFID tag store?" Accessed on: June 1, 2018. [Online]. Available: <https://www.rfidjournal.com/faq/show766>
- [16] P. Kalansuriya, "Signal processing methods for chipless RFID," Ph.D. thesis, Fac. Eng., Dept. Elec. Comp. Syst. Eng.,

- Monash Univ., Melbourne, Australia, 2017. doi: 10.4225/03/58ae40a320afe.
- [17] A. Ramos, D. Girbau, A. Lazaro, and S. Rima, "IR-UWB radar system and tag design for time-coded chipless RFID," in *Proc. 6th European Conf. Antennas and Propagation (EUCAP)*, 2012, pp. 2491–2494.
- [18] SkyRFID, "Active RFID tags—433 MHz long range RFID & real-time location system tags." Accessed on: Apr. 3, 2018. [Online]. Available: http://skyrfid.com/RFID_Active_Tag_433.php
- [19] Gao RFID, "2.45 GHz active personnel RFID card tag." Accessed on: Apr. 3, 2018. [Online]. Available: <http://gaorfid.com/product/card-tag-active-personnel-2-45-ghz-rfid/>
- [20] Electronics Notes, "Ultra wideband technology tutorial." Accessed on: June 26, 2019. [Online]. Available: <http://ultra.usc.edu/assets/002/36682.pdf>
- [21] R. S. Kshetrimayum, "An introduction to UWB communication systems," *IEEE Potentials*, vol. 28, no. 2, pp. 9–13, 2009.
- [22] Shenzhen Huwei SK Technology Co., Ltd, "1st generational ID card." Accessed on: June 5, 2018. [Online]. Available: <http://www.hw688.com/en/showpro.asp?id=1208>
- [23] Federal Communications Commission, "Radio frequency safety." (2017, July). Accessed on: 2018. [Online]. Available: <https://www.fcc.gov/general/radio-frequency-safety-0>
- [24] K. Penttilä, M. Keskilampi, L. Sydänheimo, and M. Kivikoski, "Radar cross-section analysis for passive RFID systems," *IEEE Proc.—Microw., Antennas Propag.*, vol. 153, no. 1, pp. 103–109, 2006.
- [25] P. V. Nikitin and K. S. Rao, "Theory and measurement of backscattering from RFID tags," *IEEE Antennas Propag. Mag.*, vol. 48, no. 6, pp. 212–218, 2006.
- [26] S. Preradovic, "Chipless RFID system for barcode replacement," Ph.D. thesis, Fac. Eng., Dept. Elec. Comp. Syst. Eng., Monash Univ., Melbourne, Australia, 2017. doi: 10.4225/03/587c024db56ce.
- [27] Gao RFID, "UHF RFID vehicle hang tag." Accessed on: Apr. 4, 2018. [Online]. Available: <http://gaorfid.com/product/uhf-rfid-vehicle-hang-tag/>
- [28] M. Khaliel, A. El-Awamry, A. Fawky, M. El-Hadidy, and T. Kaiser, "A novel co/cross-polarizing chipless RFID tags for high coding capacity and robust detection," in *Proc. IEEE Int. Symp. Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2015, pp. 159–160.
- [29] R. Nayak, A. Singh, R. Padhye, and L. Wang, "RFID in textile and clothing manufacturing: Technology and challenges," *Fashion Textiles*, vol. 2, no. 1, p. 9, 2015.
- [30] RFID Journal, "How many tags can be read by an RFID reader at one time?" Accessed on: June 7, 2018. [Online]. Available: <http://www.rfidjournal.com/blogs/experts/entry?8958>
- [31] Rubayet-E-Azim, "Collision, data recovery and localisation in chipless RFID," Ph.D. thesis, Fac. Eng., Dept. Elec. Comp. Syst. Eng., Monash Univ., Melbourne, Australia, 2017. doi: 10.4225/03/58ab-b7c23596b
- [32] Metacraft, "Standard RFID tags." Accessed on: June 2, 2018. [Online]. Available: <http://www.idplate.com/product/standard-rfid-tags-and-asset-property-labels/rfid-tags-rfid-labels-and-asset-tags>
- [33] XtremeRFID, (2014, 4 June 2017). "Encapsulation material." [Online]. Available: <https://xtremefid.com/products>
- [34] L. Catarinucci, R. Colella, M. D. Blasi, L. Patrono, and L. Tarricone, "Improving item-level tracing systems through ad hoc UHF RFID tags," in *Proc. IEEE Radio and Wireless Symp. (RWS)*, 2010, pp. 160–163.
- [35] A. Vena, E. Perret, and S. Tedjini, "A depolarizing chipless RFID tag for robust detection and its FCC compliant UWB reading system," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 8, pp. 2982–2994, 2013.
- [36] A. Fawky, M. Khaliel, A. El-Awamry, M. El-Hadidy, and T. Kaiser, "Novel pseudo-noise coded chipless RFID system for clutter removal and tag detection," in *Proc. IEEE Int. Conf. RFID*, 2015, pp. 100–104.
- [37] M. Chapin, "Water structure and science." Accessed on: Mar. 5, 2018. [Online]. Available: http://www1.lsbu.ac.uk/water/micro_wave_water.html
- [38] M. A. Islam and N. Karmakar, "Compact printable chipless RFID tags using polarization diversity," in *Proc. 9th European Radar Conf.*, 2012, pp. 586–589.
- [39] 4taconic.com, (2017, June 4). Microwave & RF Laminates Products [Online]. Available: <https://www.4taconic.com/page/microwave-rf-laminates-66.html>
- [40] C. Herrojo, J. Mata-Contreras, F. Paredes, A. Núñez, E. Ramon, and F. Martín, "Near-field chipless-RFID system with erasable/programmable 40-bit tags inkjet printed on paper substrates," *IEEE Microw. Compon. Lett.*, vol. PP, no. 99, pp. 1–3, 2018.
- [41] A. P. C. f. N. E. Stephen D. Holland, "RFID tags for detecting concrete degradation in bridge decks." [Online]. Available: https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1069&context=intrans_reports
- [42] Z. Zou et al., "Design and demonstration of passive UWB RFIDs: Chipless versus chip solutions," in *Proc. IEEE Int. Conf. RFID-Technologies and Applications (RFID-TA)*, 2012, pp. 6–11.
- [43] Y. Feng, L. Xie, Q. Chen, and L. R. Zheng, "Low-cost printed chipless RFID humidity sensor tag for intelligent packaging," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3201–3208, 2015.
- [44] T. Blecha, "Screen printed chipless RFID tags," in *Proc. 37th Int. Spring Seminar Electronics Technology*, 2014, pp. 143–146.
- [45] Digikey, "RFID transponders," Accessed on: June 26, 2019. [Online]. Available: <https://www.digikey.com/products/en/rf-if-and-rfid/rfid-transponders-tags/853?FV=ffe00355&quantity=0&ColumnSort=0&page=1&k=UHF+RFID&pageSize=50>
- [46] M. Zomorrod, N. C. Karmakar, and S. G. Bansal, "Introduction of electromagnetic image-based chipless RFID system," in *Proc. IEEE 8th Int. Conf. Intelligent Sensors, Sensor Networks and Information Processing*, 2013, pp. 443–448.
- [47] S. Preradovic and N. C. Karmakar, "RFID readers—A review," in *Proc. Int. Conf. Electrical and Computer Engineering*, 2006, pp. 100–103.
- [48] 3M, (2006, Sept.). "License plate production & vehicle registration systems for motor vehicle agencies." Accessed on: May 25, 2018. [Online]. Available: <http://www.samsys.com>
- [49] RF Code. Accessed on: March 5, 2018. [Online]. Available: <http://www.rfcode.com>
- [50] atlasRFIDstore.com, (2017). "Handheld RFID readers." Accessed on: March 5, 2018. [Online]. Available: <https://www.atlasrfidstore.com/handheld-rfid-readers/>
- [51] Spectra Systems. Accessed on: March 5, 2018. [Online]. Available: www.spsys.com
- [52] A. Vena, E. Perret, and S. Tedjini, "Chipless RFID tag using hybrid coding technique," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 12, pp. 3356–3364, 2011.
- [53] D. E. N. Davies, M. J. Withers, and R. P. Claydon, "Passive coded transponder using an acoustic-surface-wave delay line," *Electron. Lett.*, vol. 11, no. 8, pp. 163–164, 1975.
- [54] M. Garbati, R. Siragusa, E. Perret, and C. Halopé, "Low cost low sampling noise UWB chipless RFID reader," in *Proc. IEEE MTT-S Int. Microwave Symp.*, 2015, pp. 1–4. doi: 10.1109/MWSYM.2015.7166944.
- [55] A. Vena, E. Perret, B. Sorli, and S. Tedjini, "Toward reliable readers for chipless RFID systems," in *Proc. 31st URSI General Assembly and Scientific Symp. (URSI GASS)*, 2014, pp. 1–4. doi: 10.1109/URSI-GASS.2014.6929209.
- [56] M. Garbati, R. Siragusa, E. Perret, A. Vena, and C. Halopé, "High performance chipless RFID reader based on IR-UWB technology," in *Proc. 9th European Conf. Antennas and Propagation (EuCAP)*, 2015, pp. 1–5.
- [57] Amazon.com, "ACS NFC ACR122U RFID contactless smart IC card reader." Accessed on: Mar. 20, 2018 [Online]. Available: https://www.amazon.com/ACR122U-Contactless-Reader-Writer-Mifare/dp/B01BO3RRXE/ref=sr_1_1?ie=UTF8&qid=1490146671&sr=8-1-spons&keywords=NFC+reader&psc=1
- [58] M. A. Islam, Y. Yap and N. Karmakar, "A slotted compact printable orientation insensitive chipless RFID tag for long range applications," in *Proc. 2016 9th Int. Conf. Electrical and Computer Engineering (ICECE)*, Dhaka, Bangladesh, 2016, pp. 283–286. doi: 10.1109/ICECE.2016.7853911.

